MICROSTRUCTURAL FEATURES OF AISI 430 FERRITIC STAINLESS STEEL (FSS) WELD PRODUCED UNDER VARYING PROCESS PARAMETERS

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ABSTRACT
The after-weld properties of material are influenced by the microstructural features of the weld section which are controlled by the energy input and heat transfer factors. The welding current, travel speed and the material property govern these parameters. However, the specific influence of range of heat input rates on the microstructural features of FSS weld is hardly reported. This paper reports the microstructural features of FSS welds produced under different heat input rates. It has been observed that, irrespective of the welding condition, the primary solidification structure changed from a predominantly ferritic structure to a matrix interspersed with increasing fraction of inter-dendritic martensite in the weld metal and grain boundary martensite in the HAZ. The grain morphologies alternate between columnar and equiaxed grains depending on the welding speed within a given current. However, welding speed of 3.5mm/s appears to generally lead to the production of equiaxed grains.

Keywords: microstructural features, welding current, welding speed, TIG welding, ferritic stainless steel weld

INTRODUCTION
The ferritic stainless steel is an attractive alternative to the most often adopted austenitic stainless steel due to its higher strength, better ductility and superior corrosion resistance in caustic and chloride environments and is suitable for application in process /petrochemical, oil & gas, nuclear and power industries (Lacombe et al. 1993; Kotecki 1998; Mohandas et al. 1999). However, its application is limited because of poor ductility and low notch impact toughness (Easterling 1993). This is probably caused by the normal weld pool solidification, which permits the development of columnar grains in the re-solidified weld zone and large grain structure in the HAZ. There is also the formation of non-equilibrium phases such as inter-dendritic and grain boundary martensite due to the rapid cooling process encountered in welding. This scenario is true for welded section of almost all materials.

The microstructural features of weld metals that influence their after-weld properties are controlled by the energy input and heat transfer factors, which are governed by the welding current, travel speed and the material. The microstructures and grain morphologies determine the strength of the weldment. However, the influence of welding variables such as heat input, of grain modifier on the microstructure and welding speed and presence properties of fusion welded ferritic stainless steel has hardly been studied. These variables are critical factors in controlling weld induced microstructure and properties in weldments.

Low heat energy input welding process has been suggested (Kou & Le 1988; Greeff & du Toit 2006) as possible means of solving the problem of microstructural differentials in the various section of the weld metal and hence improved mechanical strength particularly in thin section materials. However, literature information on the range of welding current and speed that constitute low heat input rate is seldom available. Lancaster (1993) provided a hint of the low welding current as 50-170A but no range was provided for welding speed. Thus, the present attempt discuss the microstructural features of ferritic stainless steel welds...
produced under different heat input and welding speed measured in terms of the heat input rates.

EXPERIMENTAL MATERIALS AND PROCEDURE

MATERIALS PREPARATION

The workpiece used in the present investigation is AISI 430 ferritic stainless steel 1.5mm thick sheet supplied in the cold rolled and annealed condition by Senco Sans, Malaysia, sole agent Testfabrics Inc. USA. The nominal chemical composition and microstructure of the steel are given in Table 1 and Figure 2 respectively. The as-received parent metal consists of elongated ferrite grains with carbides along the grain boundaries and within the ferrite grains. Ferritic stainless steel coupons of size 65x25x1.5mm were prepared using Sunfluid hydraulic shear machine model 300 D/10 and pre-cleaned with acetone preparatory to welding.

EXPERIMENTAL DETAIL

Autogenous full bead on plate welds were made via a programmable TIG welding machine with a traversing carriage of adjustable travel speed using DC straight polarity mode with thoriated tungsten electrode of diameter 2.4mm in 99.9% purity argon shielding gas at a flow rate of 0.12dm$^{3}$/s. The electrode tip angle was made constant at 30°. Different levels of current 50-160A and welding speed 1-3.5mm/s were investigated while the arc voltage was kept constant at 30V. Details of the investigation are illustrated in Table 2 and Figure 1 respectively.

Specimens were cut from the transverse section and further prepared for optical metallography. In the present study, an etchant made up of a mixture of 3ml of glycerol, 5ml of HCL and 1ml of HNO$_3$ was used to selectively attack the 0.25 micron diamond paste polished weld specimen. The etchant was used immediately after preparation and discarded once the colour of the solution turns orange. The microstructures of the etched welded specimens were examined using digitised light optical microscopy (LOM) system, NIKON EPILIGHT model 200.

In the present study, the heat input rate per unit length of the weld is evaluated from the relationship provided by Easterling (1993)

$$H/d = \frac{\eta I V}{v}$$  \hspace{1cm} (1)

where I is the welding current, V is the arc voltage kept constant at 30V, v is the welding speed and $\eta$ is the arc efficiency. The efficiency in the present study is taken as 0.48, the upper bound of TIG welding efficiency range (22-48%).

The Kaltenhausser ferrite factor is calculated from the expression provided by Kaltenhauser (1971)

$$KFF = Cr + 6Si + 8Ti + 4Mo + 2Al - (40(C + N) - 2Mn - 4Ni)$$  \hspace{1cm} (2)

Figure 1: Experimental setup, (a) welding rig (b) weld specimens at different welding conditions

The Kaltenhausser ferrite factor composite of the welding current and welding speed. The material microstructural response to welding conditions of current and speed is thus evaluated more appropriately by using the heat input rate per unit length of weld. This is the parameter that is used to characterize welding process in terms of heating rate, cooling rate and at times, the weld pool size. The welding speed is a measure of the dwell time or what is more generally refer to as the residence time, and the time spend above the recrystallisation temperature determines the degree of grain coarsening that develops in the weld metal.

Lancaster (1993) classified welding current range 50-170A as relatively low heat input process. The range of heat input per unit length considered in the present work is highlighted in Table 2. Heat input rates per unit length of weld between 205J/mm and 2.3KJ/mm corresponding to welding current 50-160A and speed 1-3.5mm/s were considered.

Figure 2 is the microstructure of the as-recieved AISI 430 ferritic stainless steel. The micrograph consist of streaks of martensite in ferrite matrix. The presence of C and some other residual elements in solid solution with Cr in the ferritic stainless steel implies the expansion of the Gamma ($\gamma$) loop. This increases the formation of austenite in the high temperature transformation zone (A$_t$) which invariably increases the tendency to form martensite during fast cooling, a scenario approximated
by fusion welding. The tendency to form martensite in weld metal is evaluated using the Kaltenhauser ferrite factor (KFF). The research material has a KFF of 14.7 which is a value less than the 17 given by Kaltenhauser (1971) over which austenite will not form in the high temperature zone. Thus, in the present investigation, martensite is present both in the weld metal and the HAZ.

The micrographs at the different values of heat input rate is given in Figures 3-14. In each of the micrographs, three distinct phases manifest. These are the base metal, the HAZ and the FZ.

The figures irrespective of the heat input rate show the presence of columnar grains in the fusion zone with interdendritic martensite and grain boundary martensite in the HAZ. However, the fraction and distribution of the columnar grains and martensite changes as the heating rate changes. The martensite in the fusion zone is well defined with continuous grain elongation.

Within a particular welding current, the grains of the phases changes in morphologies from elongated grains to in some instances, abutted equiaxed grains as the welding speed increases. The welding speed of 3.5 mm/s appears to generate equiaxed grains (Figures 3-

<table>
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<th>Material Spec.</th>
<th>Composition</th>
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<tr>
<td>AISI 430</td>
<td>C  Cr  Ni  Si  Mn  Mo  Cu  P  S  N  Ti</td>
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<td>0.12</td>
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| Table 2: Tabular listing of heat input and welding speed for experimental runs |
|----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| S/N | Weld No | Heat Input (I*V) | Heat Input rate/unit length of weld (J/mm) at different Welding speed(mm/s) |
|     |       |                 | 1    | 1.5   | 2     | 2.5   | 3     | 3.5 |
| 1   | FSS 430_50 | 50 A X 30V | 720  | 480   | 360   | 288   | 240   | 205.7 |
| 2   | FSS 430_60 | 60 A X 30V | 864  | 576   | 432   | 345.6 | 288   | 246.8 |
| 3   | FSS 430_70 | 70 A X 30V | 1008 | 672   | 504   | 403.2 | 336   | 288   |
| 4   | FSS 430_80 | 80 A X 30V | 1152 | 768   | 576   | 460.8 | 384   | 329.1 |
| 5   | FSS 430_90 | 90 A X 30V | 1296 | 864   | 648   | 518.4 | 432   | 369.9 |
| 6   | FSS 430_100 | 100 A X 30V | 1440 | 960   | 720   | 576   | 480   | 414   |
| 7   | FSS 430_110 | 110 A X 30V | 1584 | 1056  | 792   | 633.6 | 528   | 452.5 |
| 8   | FSS 430_120 | 120 A X 30V | 1728 | 1152  | 864   | 691.2 | 576   | 493.7 |
| 9   | FSS 430_130 | 130 A X 30V | 1872 | 1248  | 936   | 748.8 | 624   | 534.8 |
| 10  | FSS 430_140 | 140 A X 30V | 2016 | 1344  | 1008  | 806.4 | 672   | 576   |
| 11  | FSS 430_150 | 150 A X 30V | 2160 | 1440  | 1080  | 864   | 720   | 617.1 |
| 12  | FSS 430_160 | 160 A X 30V | 2304 | 1536  | 1152  | 921.6 | 768   | 658.24 |
RESULTS AND DISCUSSION

Figure 2: As-received AISI 430 ferritic stainless steel, streak of martensite in ferrite matrix

Figure 3: Microstructure at current of 50A and different speeds (a) 1 (b) 1.5 (c) 2 (d) 2.5, (e) 3 and (f) 3.5mm/s

Figure 4: Microstructure at current of 60A and different speeds (a) 1 (b) 1.5 (c) 2 (d) 2.5, (e) 3 and (f) 3.5mm/s

Figure 5: Microstructure at current of 70A and different speeds (a) 1 (b) 1.5 (c) 2 (d) 2.5, (e) 3 and (f) 3.5mm/s

Figure 6: Microstructure at current of 80A and different speeds (a) 1 (b) 1.5 (c) 2 (d) 2.5, (e) 3 and (f) 3.5mm/s
Figure 7: Microstructure at current of 90A and different speeds (a) 1 (b) 1.5 (c) 2 (d) 2.5, (e) 3 and (f) 3.5mm/s

Figure 8: Microstructure at current of 100A and different speeds (a) 1 (b) 1.5 (c) 2 (d) 2.5, (e) 3 and (f) 3.5mm/s

Figure 9: Microstructure at current of 110A and different speeds (a) 1 (b) 1.5 (c) 2 (d) 2.5, (e) 3 and (f) 3.5mm/s

Figure 10: Microstructure at current of 120A and different speeds (a) 1 (b) 1.5 (c) 2 (d) 2.5, (e) 3 and (f) 3.5mm/s
Figure 11: Microstructure at current of 130A and different speeds (a) 1 (b) 1.5 (c) 2 (d) 2.5, (e) 3 and (f) 3.5mm/s.

Figure 12: Microstructure at current of 140A and different speeds (a) 1 (b) 1.5 (c) 2 (d) 2.5, (e) 3 and (f) 3.5mm/s.

Figure 13: Microstructure at current of 150A and different speeds (a) 1 (b) 1.5 (c) 2 (d) 2.5, (e) 3 and (f) 3.5mm/s.

Figure 14: Microstructure at current of 160A and different speeds (a) 1 (b) 1.5 (c) 2 (d) 2.5, (e) 3 and (f) 3.5mm/s.
Low heat input welding has been variously suggested as the welding condition that can guarantee control of grain size in both the HAZ and the weld metal in thin section material. This parameter is measured as a 10fs). This observation is reinforced with the fact that the welding speed is a measure of the residence time. At higher welding speed for a given welding current, the time spent above the coarsening temperature is very short and thus the grains in the HAZ and in the weld metal are less coarse relative to the lower welding speed. Infact, some grain refinements were observed in Figures 3-6fs. However, between welding speed of 1mm/s and 2.5mm/s, the grains structure alternate between columnar and equaixed structure. As the heat input rate increases, the grains generally becomes bigger. This is because, at high heat input rate the thermal cycle is longer and tend to generate coarser structure (Kou 2003). The FZ and the HAZ, profiles increases as the welding current increases and for a given current, the FZ and the HAZ decreases as the welding speed increases. However, beyond, welding current of 120A, it appears the welding speed has no influence on the FZ and HAZ. Complete XRD and EDS characterization of the welds at the different heat input rates is currently being undertaken for phase and phase fraction analysis together with micro hardness evaluation. The present LOM analysis, however, has revealed the dependence of grain morphologies on the total heat input rate.

CONCLUSION

The microstructural feature of AISI 430 ferritic stainless steel weld produced under different range of heat input rates has been investigated in terms of phases and morphologies. It has been observed that irrespective of the welding condition, the primary solidification structure changed from a predominantly ferritic structure to a matrix interspersed with increasing fraction of interdendritic martensite in the weld metal and grain boundary martensite in the heat affected zone. The martensite distribution in the steel falls within the Kaltenhauser ferrite factor for the formation of austenite in the high temperature transformation zone. The grain morphologies alternates between columnar and equiaxed grains depending on the welding speed within a given current. However, welding speed of 3.5mm/s appears to generally lead to the production of equiaxed grains. AT welding current below the critical level, the microstructural features of the weld is influenced by the combination of welding current and speed. This implies that below the critical welding current value, the mechanical properties of ferritic steel weld might be influenced by both the welding current and the speed.

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REFERENCES


